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Evaporation Performance Analysis for Water Retentive Material Based on Outdoor Heat Budget and Transport Properties

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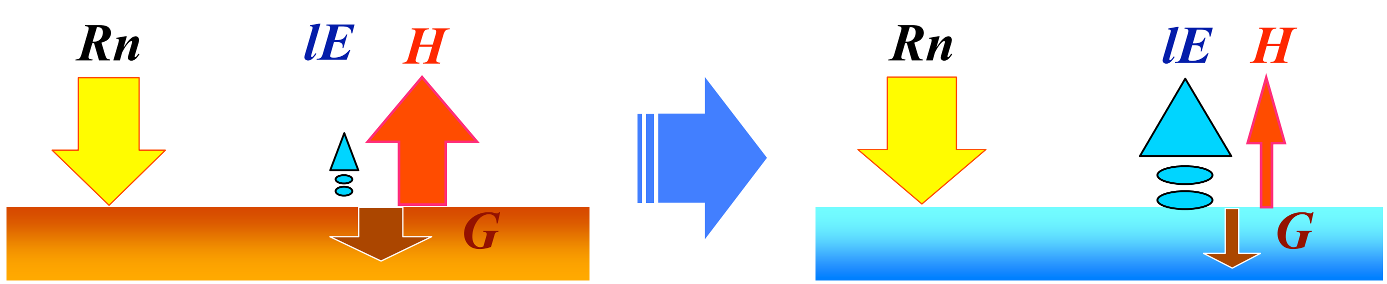
Background

Recently, urban heat island is remarkable at almost metropolises in Japan, and countermeasures for the phenomenon are urgently demanded.

Paving with water retentive material on streets or roads

To diminish sensible heat flux and reduce air temperature by absorbing latent heat of water retained in the material.

It is necessary for the promotion of the water retentive material that the method of performance evaluation of the material is established.



Objectives

- To evaluate the evaporation performance of water retentive material outdoors in the condition simulated pavement with the material.
- To evaluate the evaporation efficiency by measuring the heat budget on the surface of material.
- To measure heat and moisture transport properties and apply them to the numerical analysis in order to investigate the evaporation behavior in detail.

Field Measurement

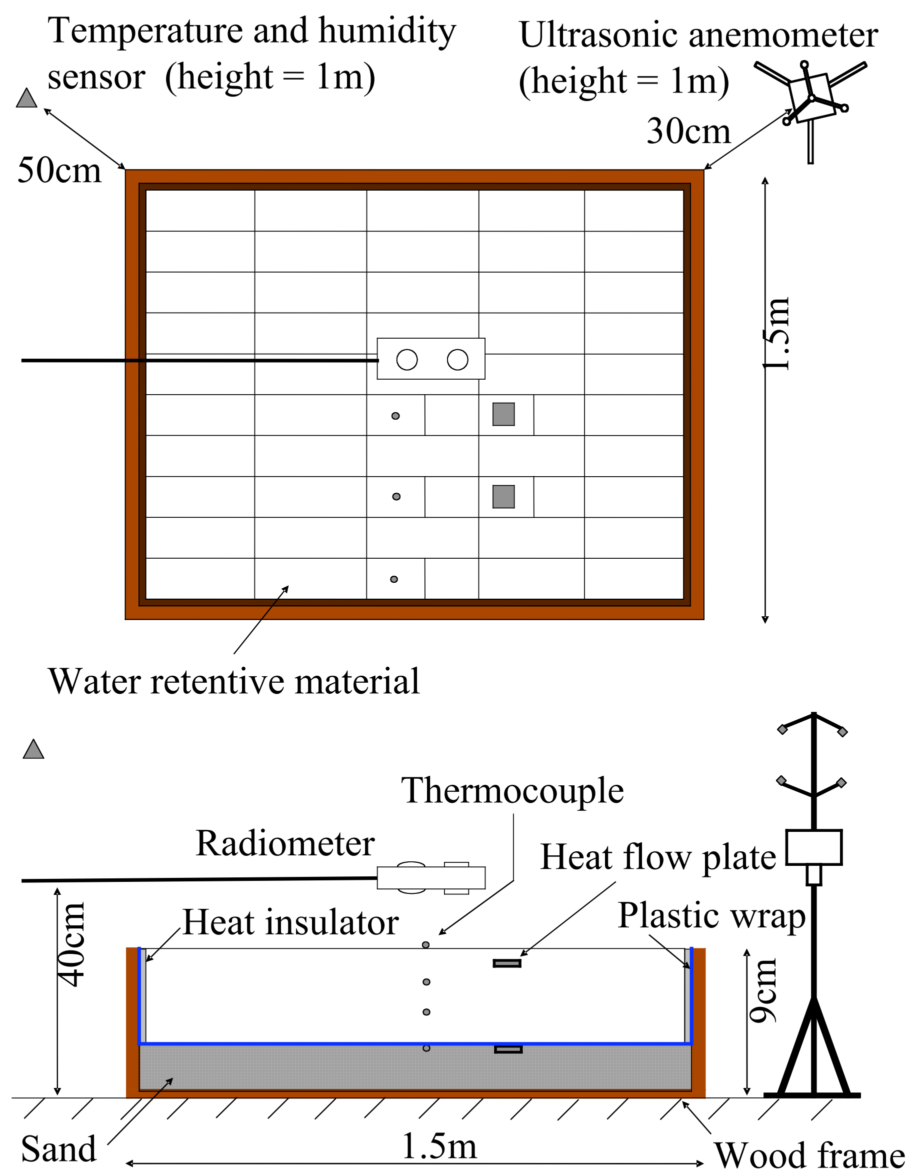
Measuring object

- 50 water retentive material blocks in a wood frame
- Size: 1.5m x 1.5m
- Sand layer is laid by assuming pavement

Measuring items

- Surface and internal temperatures of water retentive material with thermocouple
- Conductive heat flows near surface and at the bottom of material with heat flow plates
- Net radiation
- Air temperature and relative humidity
- Wind velocity

Data sampling rate: 1/20 sec^{-1}
Averaging time: 10 minutes



Field Measurement

Water retentive material

Porous media

Raw materials

Recycled material: 80%

Stone powder (Ooyaishi), wasted molding sand, and etc.

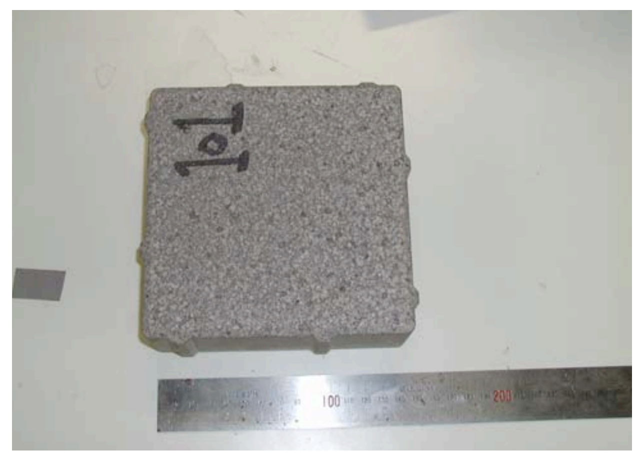
Clay: 20%

Porosity: 24.1%

Water retention: 12.1 l/m^3

Size: W300mm H150mm D50mm

W150mm H150mm D50mm



Field Measurement

Measurement site:

Open terrace in Osaka Prefecture University,

Sakai, Osaka

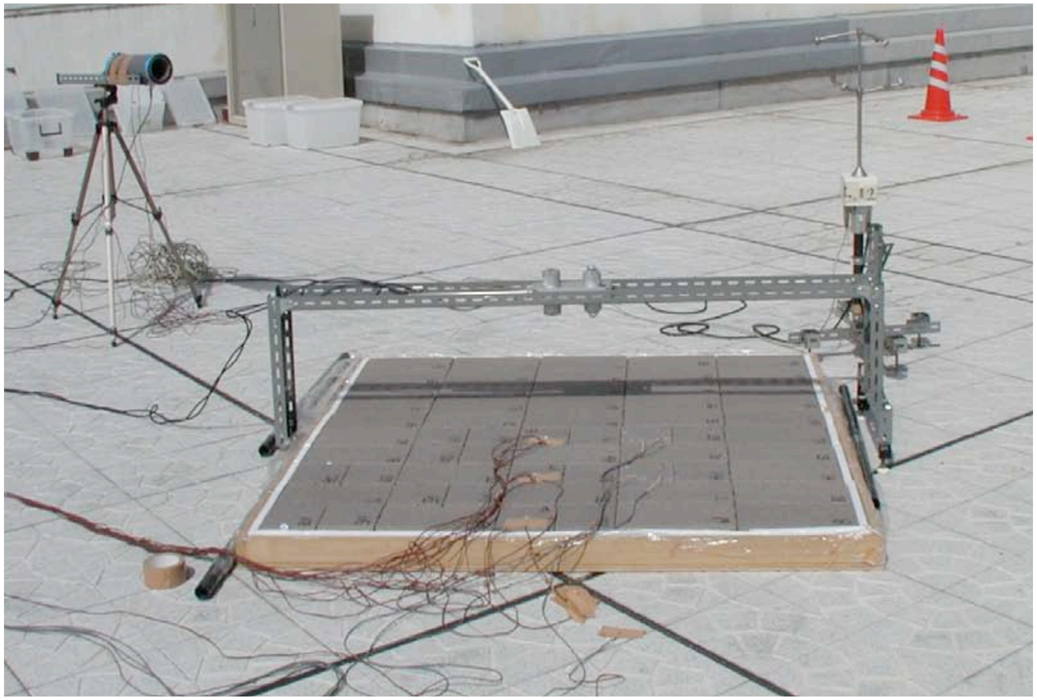
Date and measuring condition:

Case 1:

- Sep. 11, 2007
- Full wet condition

Case 2:

- Jul. 31, 2008
- After drying for one day



Calculation of Evaporation Efficiency

Evaporation efficiency: β

$$lE = Rn - H - G$$

$$E = lE / l$$

$$\beta = \frac{E}{k(q_{sat}(T_{sur}) - q_{air})}$$

Rn : Net radiation

lE : Latent heat flux

H : Sensible heat flux

G : Conductive heat flux into material

E : Evaporation rate

l : Latent heat of water

$q_{sat}(T_{sur})$: Saturated specific humidity of water surface based on surface temperature

q_{air}: Specific humidity of atmosphere

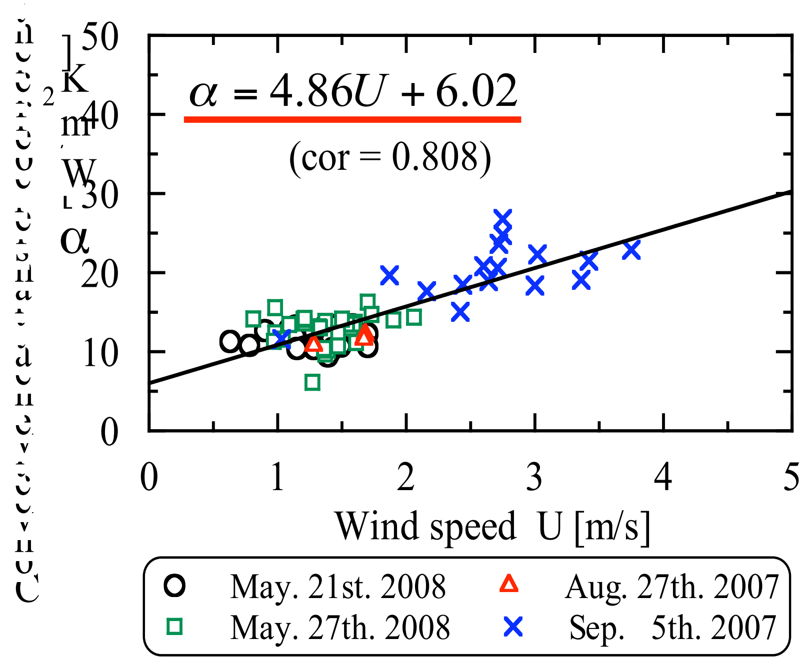
k : mass transfer coefficient

The relation between wind speed and convective heat transfer coefficient for measuring sensible heat flux is pre-estimated in the dry condition.

$$H = Rn - G \qquad \alpha = \frac{H}{T_{sur} - T_{air}}$$

α : Convective heat transfer coefficient

T_{sur}:Surface temperature, T_{air}: Air temperature

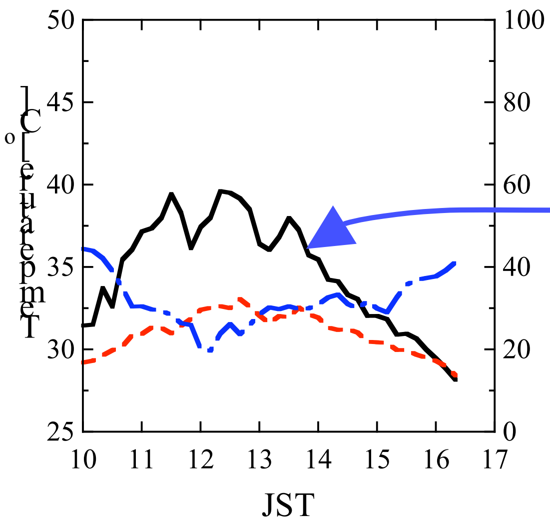


Measured Results

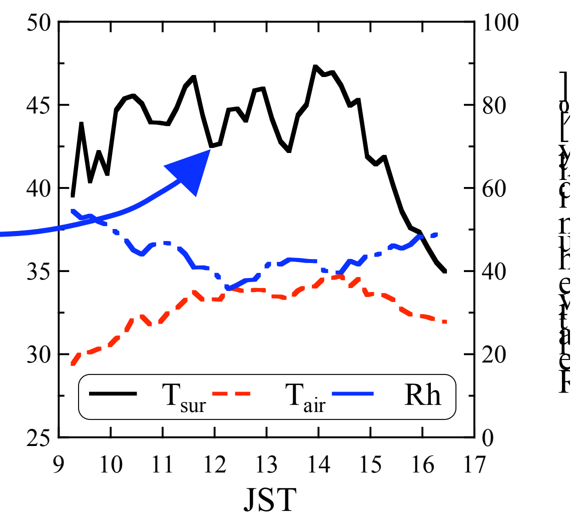
Case 1: Full wet (Sep. 11th, 2007)

Case 2: After drying for one day (Jul. 31st, 2008)

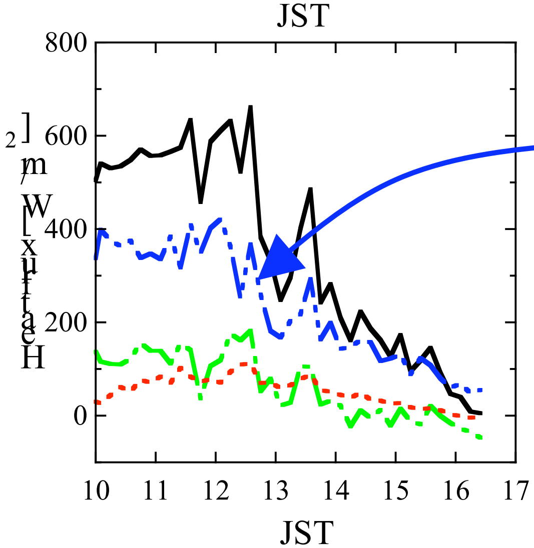
Air and surface temperature



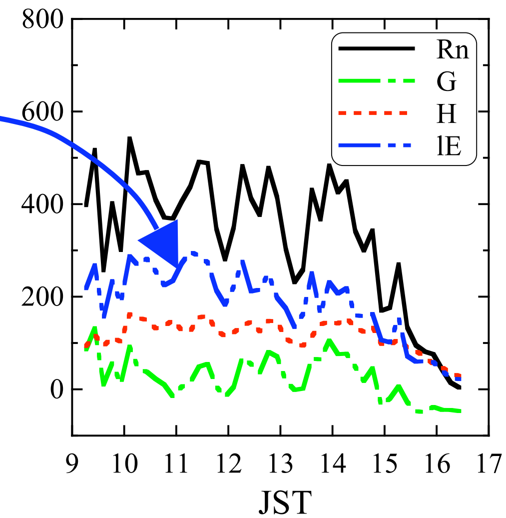
Although Rn in the morning of Sep. 11th is higher than that of Jul. 31st, the surface temperature in full wet condition is lower than that after drying condition.



Heat budget



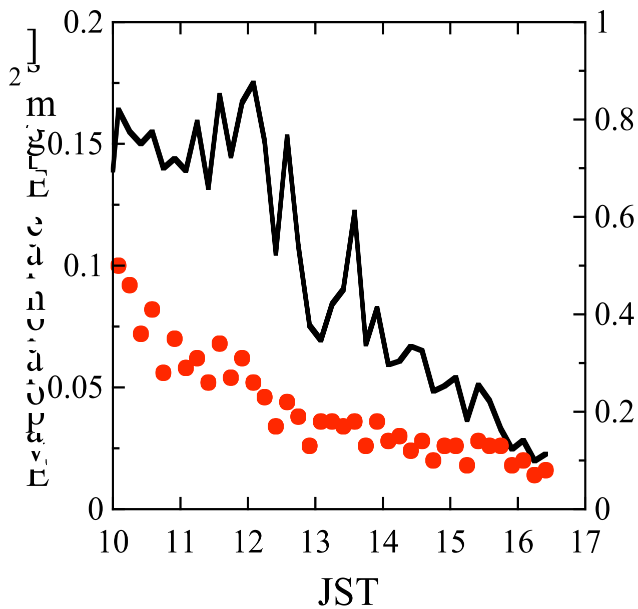
Latent heat flux lE occupies most of heat budget in both cases.



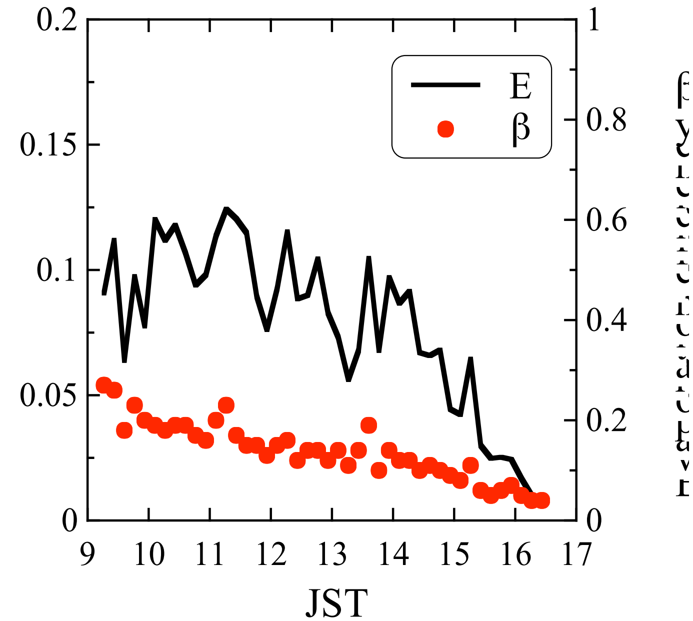
The ratio of latent heat flux to net radiation in case 2 is smaller than that in case 1. On the other hand, the ratio of sensible heat flux in case 2 is twice larger.

Measured Results

Case 1: Full wet
(Sep. 11th, 2007)



Case 2: After drying for one day
(Jul. 31st, 2008)



Evaporation rate
Evaporation efficiency

E and β after drying is lower than those in wet condition.

It is revealed that the effect of surface temperature decreases by water retention and the evaporation efficiency deteriorates as water retentive material becomes drier.

It is necessary to sustain the evaporation by water supply and to construct simultaneously water supply system in utilization of water retentive material.
For this purpose, numerical analysis of heat and moisture transport inside of material is needed.

Fundamental Equations

Moisture conservation

$$\rho_w\left(\frac{\partial\psi}{\partial\mu}\right)\frac{\partial\mu}{\partial t}=\frac{\partial}{\partial x}\left[\lambda'_\mu\left(\frac{\partial\mu}{\partial x}-g\right)\right]+\frac{\partial}{\partial x}\left(\lambda'_T\frac{\partial T}{\partial x}\right)$$

Energy conservation

$$c\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[l\lambda'_{\mu g}\left(\frac{\partial\mu}{\partial x}-g\right)\right]+\frac{\partial}{\partial x}\left((\lambda+l\lambda'_{Tg})\frac{\partial T}{\partial x}\right)$$

ψ : volume moisture content
μ : moisture chemical potential
ρ : density
ρ_w : density of water
λ : thermal conductivity
P_{vS} : saturated vapor pressure
K : hydraulic conductivity
λ' : moisture conductivity

Estimate relation

$$\lambda'_{Tg}=\underline{\lambda}'e^{\frac{\mu}{R_vT}}\left(\frac{\partial P_{vS}}{\partial T}-P_{vS}\frac{\mu}{R_vT^2}\right)\qquad\lambda'_{\mu g}=\lambda'_{Tg}\left[1\Bigg/\left(\frac{R_vT\frac{\partial P_{vS}}{\partial T}}{P_{vS}}-\frac{\mu}{T}\right)\right]$$

$$\lambda'_\mu=\lambda'_{\mu g}+\lambda'_{\mu l},\quad\lambda'_{\mu l}=\underline{K}\rho_w/g\qquad\lambda'_T=\lambda'_{Tg}+\lambda'_{Tl},\quad\lambda'_{Tl}=0$$

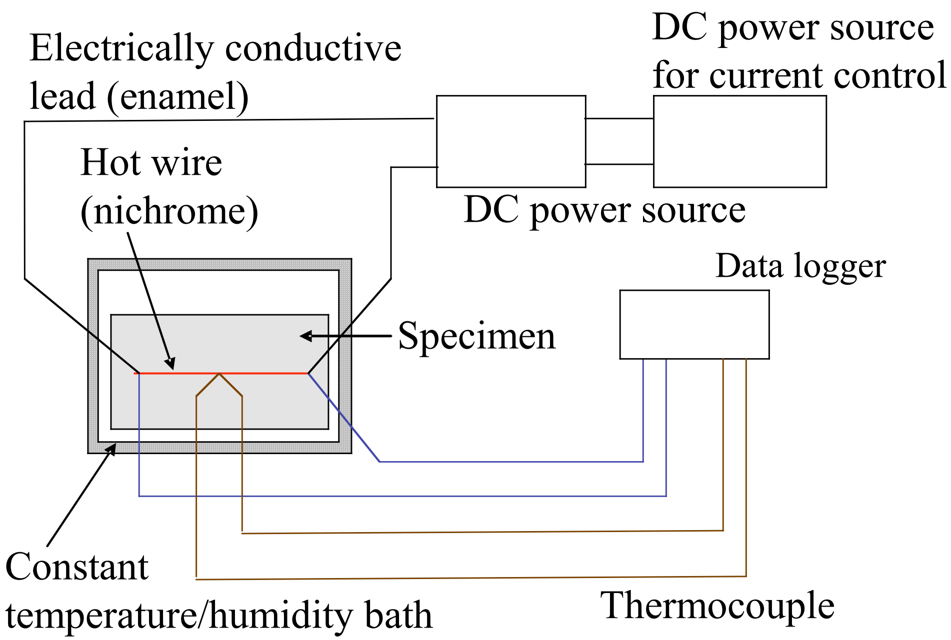
λ'_μ: moisture conductivity related to μ gradient

λ'_T: moisture conductivity related to temperature gradient

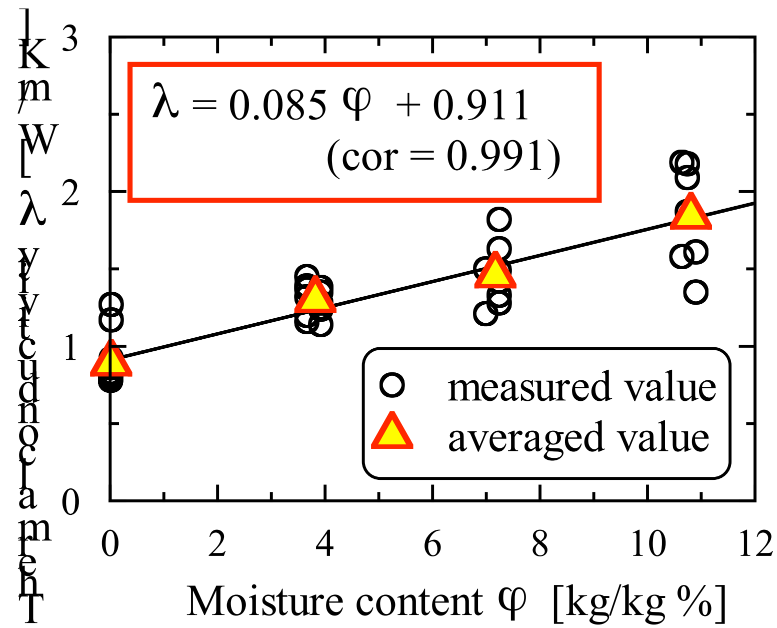
Evaluation of Transport Properties

Thermal Conductivity λ

Unsteady hot-wire method based on JIS R2616



Schematic of measurement instrument

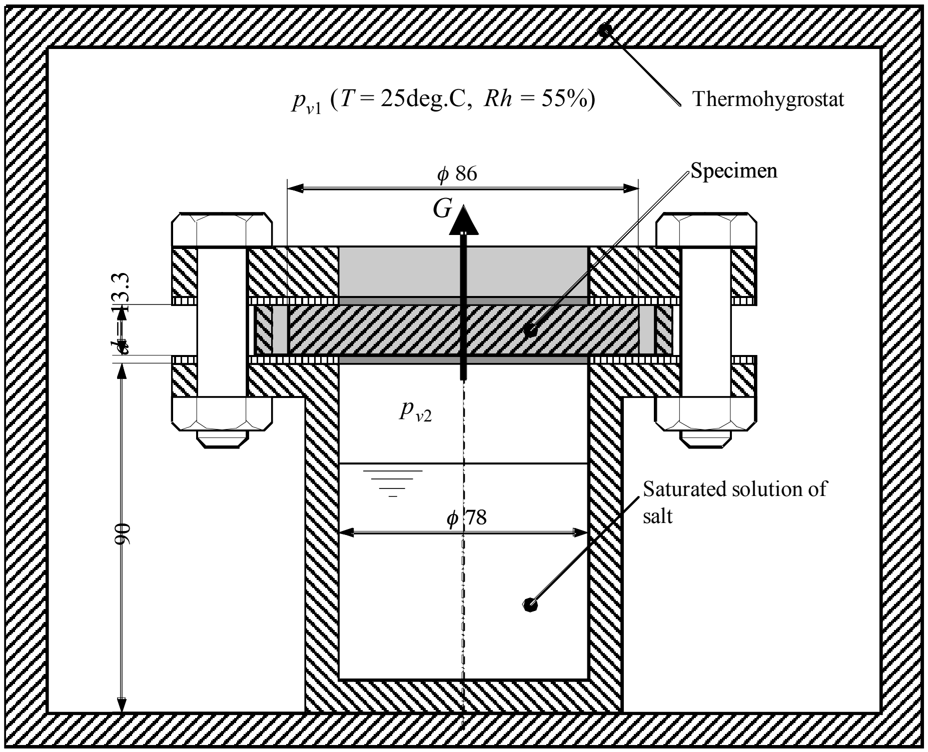


Relation between thermal conductivity
and moisture content of material

Evaluation of Transport Properties

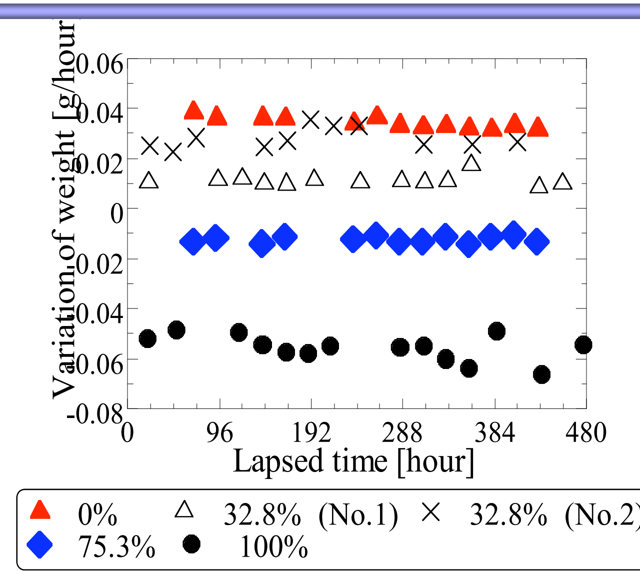
Moisture Conductivity ë′

Using saturated salt solution based on JIS A1324

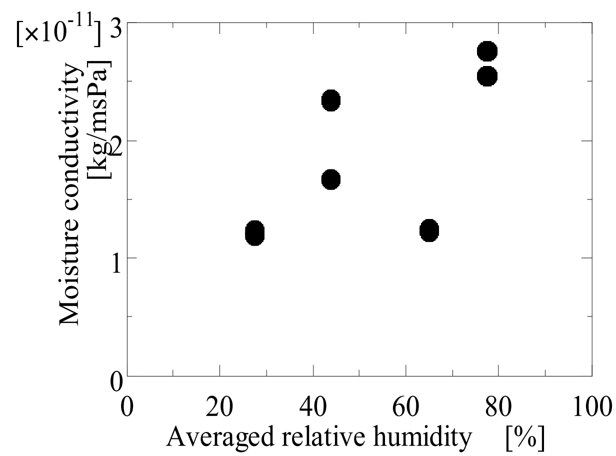


Schematic of measurement instrument

Average
<u>1.96 x 10^{-11} kg/msPa</u>



Weight change per unit time

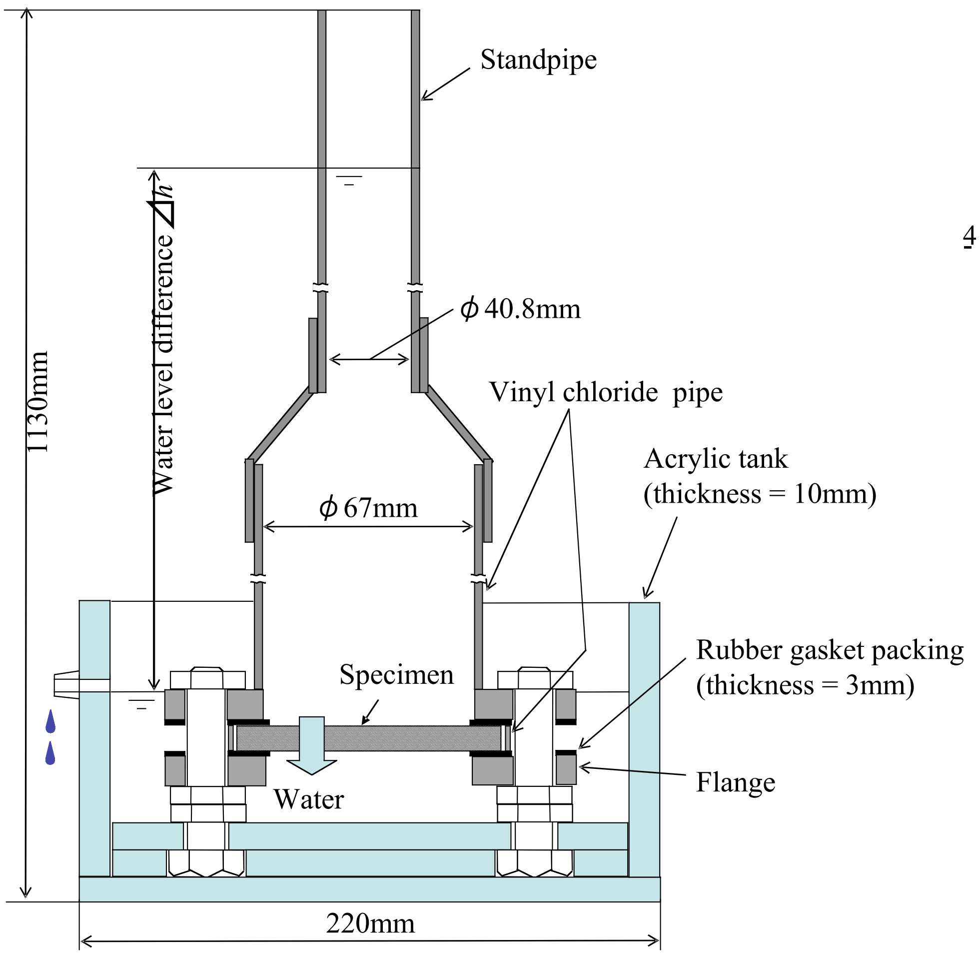


Measured result of moisture conductivity

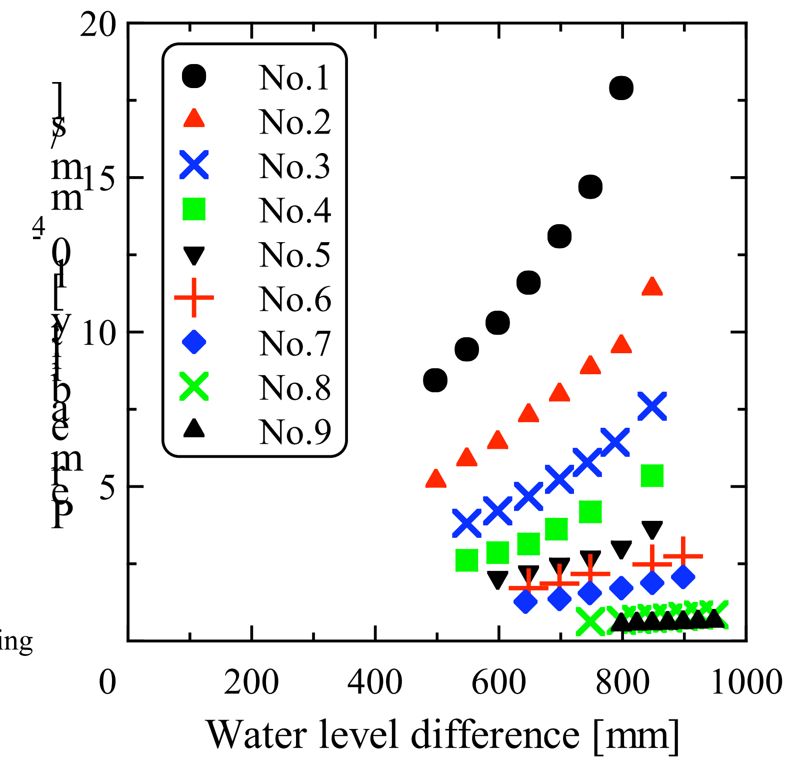
Evaluation of Transport Properties

Hydraulic Conductivity *K*

Falling head permeability test based on JIS A1218



Schematic of measurement instrument



Measured result of hydraulic conductivity

$\boxed{K = \underline{6.12\times10^{-5}\ \mathrm{mm/s}}}$

Numerical Conditions

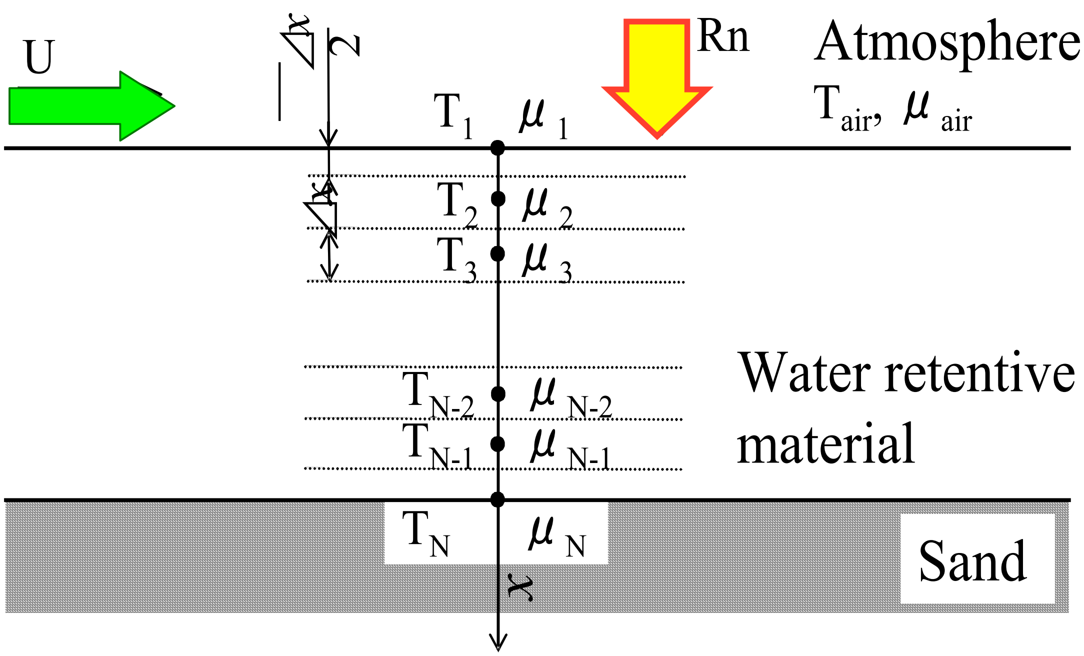
Discretization of fundamental equations using 2nd order central difference for diffusive terms.

Euler explicit method for time marching

Net radiation: Rn , Wind speed: U ,

Air temperature: T_{air} , Relative humidity: RH

(Chemical potential of moisture in air: μ_{air})



$\Delta x = 1\text{mm}$

$\Delta t = 10\text{ms}$

Initial and Boundary Conditions

Initial profiles of

- Temperature: linear interpolation of measured values
- Moisture chemical potential: uniform profile based on bulk water content at the beginning of measurement and water retention curve modeled by van Genuchten

Boundary condition of top surface

$$-\lambda'_{\mu}\left(\frac{\partial \mu}{\partial x}-g\right)-\lambda'_{T}\frac{\partial T}{\partial x}=\alpha'_{\mu}\left(\mu_{air}-\mu_{sur}\right)+\alpha'_{T}\left(T_{air}-T_{sur}\right)$$

$$-\lambda\frac{\partial T}{\partial x}-l\left[\lambda'_{\mu g}\left(\frac{\partial \mu}{\partial x}-g\right)+\lambda'_{Tg}\frac{\partial T}{\partial x}\right]=l\alpha'_{\mu}\left(\mu_{air}-\mu_{sur}\right)+\left(\alpha+l\alpha'_{T}\right)\left(T_{air}-T_{sur}\right)+Rn$$

$$\alpha'_{\mu}=\alpha'_{m}\frac{\partial P_{v}}{\partial \mu}\qquad \alpha'_{T}=\alpha'_{m}\frac{\partial P_{v}}{\partial T}\qquad \frac{\alpha}{\alpha'_{m}C\rho R_{v}T}=1$$

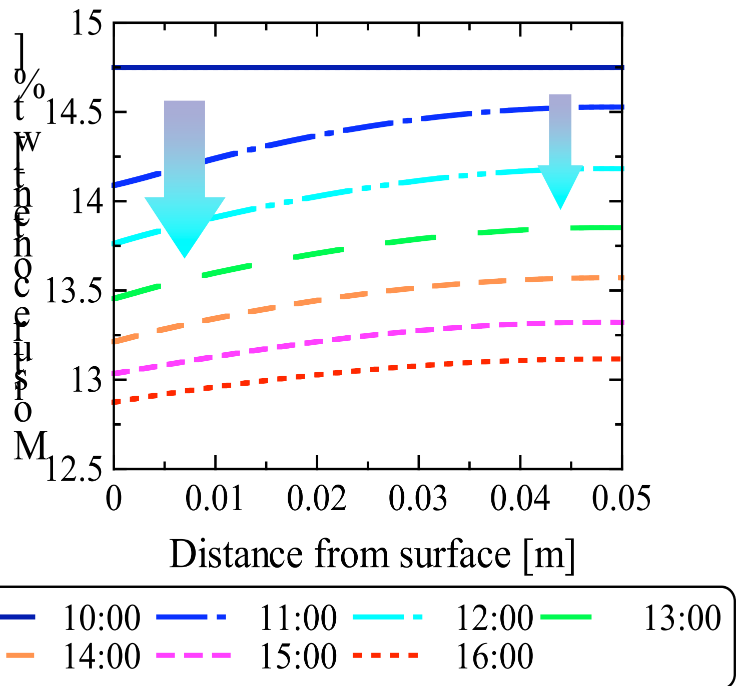
Boundary condition of bottom surface

- Measured temperature
- Moisture transport: impermeable

Numerical Results

Input data: Measured value in Sep. 11th, 2007

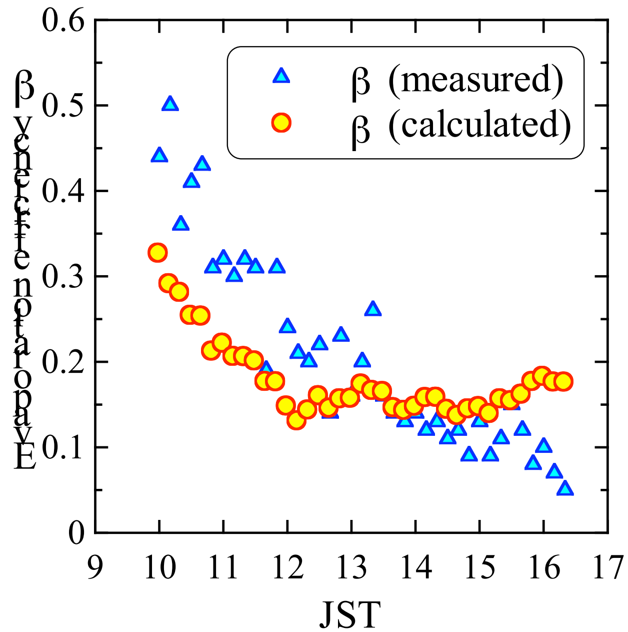
Moisture content profile in material



Evaporation rate at the material surface is faster.

Moisture content gradually decreases with the progress of surface drying. Evaporation rate is the largest at the beginning of drying and decreases with the lapse of time.

Evaporation efficiency



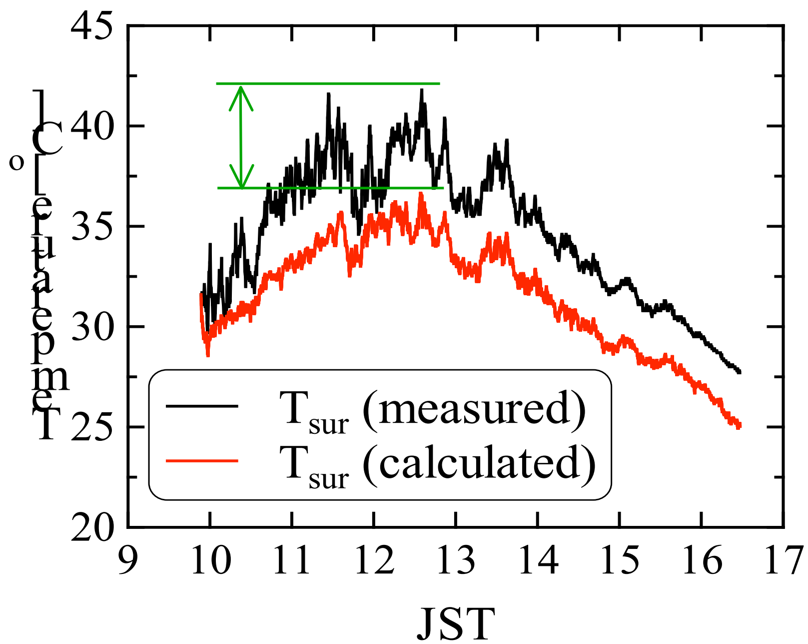
Evaporation efficiency is the largest at the beginning, and decreases with the lapse of time, which agrees with the result of field measurement.

Bulk moisture content at the end of measurement:

Calculation:	12.9wt%
Measurement:	11.6wt%

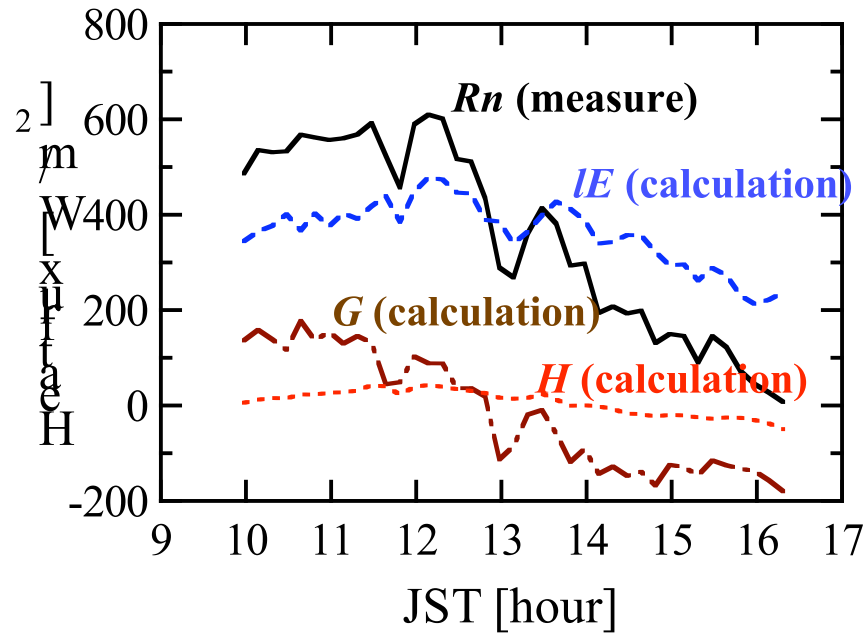
Numerical Results

Surface temperature



Calculated temporal change of temperature quantitatively agrees with measured one, but the value of calculated temperature is about 5deg.C lower than measured temperature.

Calculated Heat budget



Latent heat flux *lE* at the top surface is overestimated, and sensible heat flux and conductive heat flux are underestimated.

The numerical model using in this study can express internal moisture transfer of the water retentive material, but remains scope for improvement in heat transfer.

Summary

1. The effect of surface temperature of water retentive material decreases by water retention, and the evaporation efficiency deteriorates as water retentive material becomes drier. Evaporation efficiency can be applied for the performance evaluation of water retentive material.

2. Numerical analysis using simultaneous heat and moisture transfer equations can express internal moisture transfer of the water retentive material, but remains scope for improvement in heat transfer because of overestimation of latent heat flux by evaporation on the material surface.

Water Retentive Material

Raw materials

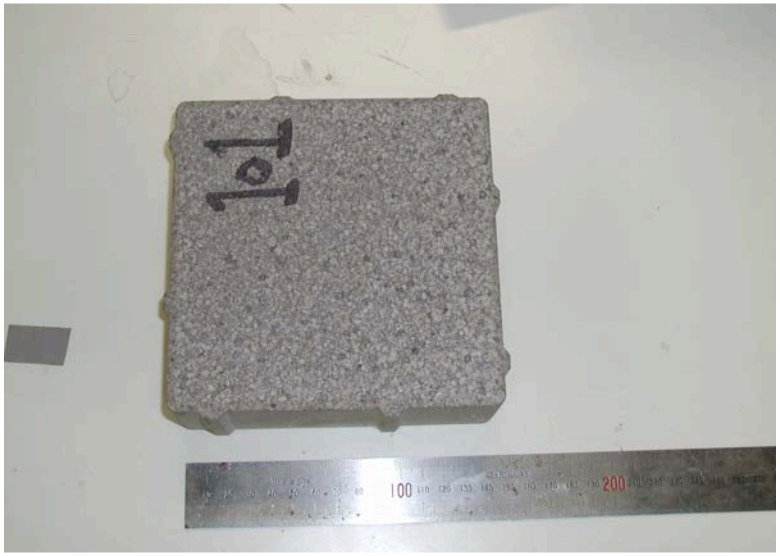
Recycled material: 80%

Stone powder (Ooyaishi), wasted molding sand, and etc.

Clay: 20%

Properties in catalog
($300 \times 150 \times 50 mm^3$)

	Measured value	Method
Water absorption	15%	JISA5209
Water retention	$12\ l / m^3$	Calculation



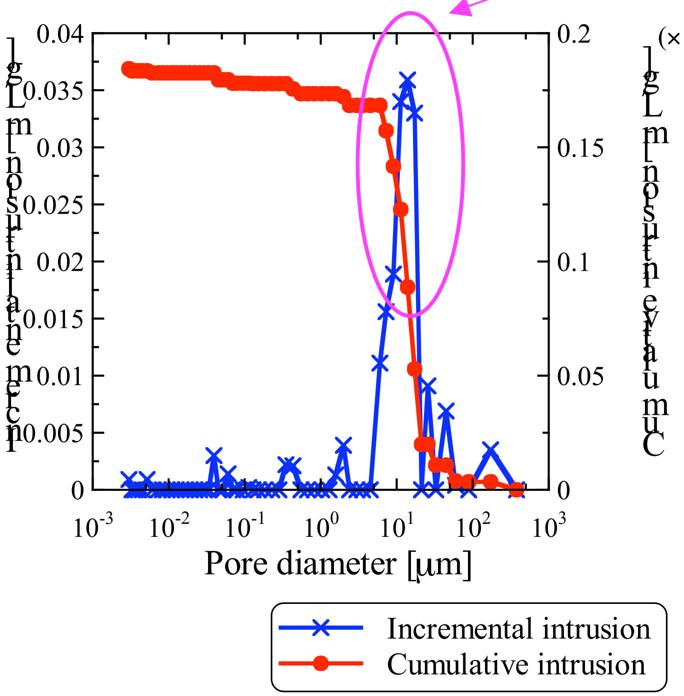
Pore Diameter Size Profile

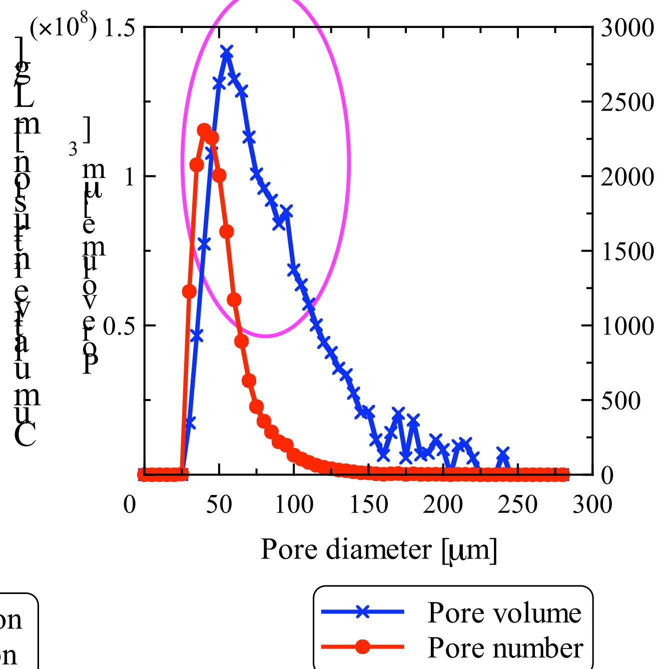
Measurement of Pore diameter size profile of water retentive material
wity Mercury porosimeter and X-ray CT

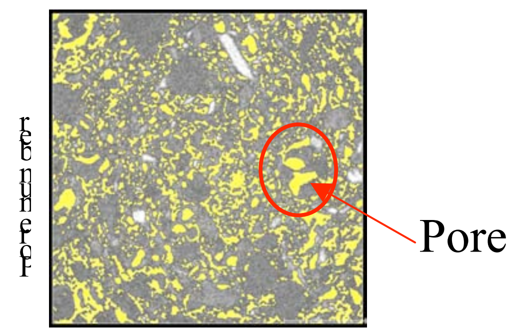
(Measured in JFCC)

Peak of Pore diameter size profile

10～100μm size pore is dominant







X-ray CT image

(Binarization processing image)

Mercury porosimeter

X-ray CT image

(Porosity: 30.02%)

(Porosity: 27.54%)